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Tailoring the ultra-soft magnetic properties of sputtered FineMET thin films for high-frequency power applications

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Abstract. This paper presents sputtered FineMET thin films with high saturation magnetic flux density and ultra-soft magnetic properties by maintaining an in-plane magnetization reversal process. The magnetic properties of FineMET thin films were investigated as a function of film thickness (40-517 nm) and annealing temperature (200-400 ºC). The hysteresis loop study reveals that the films with low thickness (40 –316 nm) were perpendicularly magnetized in the as-deposited state. The ultra-soft magnetic properties (H_c=3 A/m) of the films were tailored by a thermal annealing process. A high relative permeability (μ_r) of 1763 of these films with a good loss performance up to 1 GHz, makes them attractive for high-frequency power applications.

1. Introduction

Magnetic cores with versatility in soft magnetic properties are highly anticipated in modern energy storage and transferring devices for high-frequency applications [1, 2]. The next generation of miniaturized power electronic devices requires cores with high magnetic flux density, high resistivity, and ultra-low coercivity along with ease of manufacturability [1, 2]. Amorphous and nanocrystalline materials exhibit excellent soft magnetic properties and high electrical resistivity (ρ) as compared to their crystalline counterparts, which make them a potential candidate [3, 4]. These materials are well investigated in bulk form, however, the study of these alloys in integrated thin films form that retain their exceptional properties is a recent area of research [4]. Reports suggest the soft magnetic properties of these materials in thin films are significantly poorer as compared to their bulk form [4, 5]. One of the important factors responsible for such a deterioration in magnetic properties is the generation of internal stress/strain during the fabrication process [5]. In the present work, we report the tailored soft magnetic properties of sputtered FineMET thin films with ultra-low coercive losses typically seen in their bulk form. The high magnetic flux density (1.8 T) and large ρ (145 μΩcm) of FineMET alloy are beneficial for power electronic device miniaturization.

2. Experimental Methods

Amorphous films of FineMET ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$, atomic %) alloy with a thickness of 40-517 nm, were deposited using DC-magnetron sputtering from a single alloy target. The films were deposited on the Si wafers. Prior to the deposition of films, an adhesive layer of 20 nm of Ti was deposited. The DC-power to the target was fixed at 100 W. The structure of the films was investigated using X-ray diffraction (XRD). The films were annealed for 60 min in an inert atmosphere. In-plane hysteresis loops were studied using a SHB (MESA 200 HF) B-H loop tracer. The high-frequency relative permeability (μ_r) was measured by Ryowa permeameter (PMM 9G).

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3. Results and Discussion

The in-plane magnetic hysteresis loops of different films (40-517 nm) were performed at room temperature (Fig. 1). The saturation magnetic flux density of the 517 nm film was estimated to be 1.8 T for a 100 mm wafer. Figure 1 illustrates that the shape of the hysteresis loops, coercivity (H_c) and anisotropic field (H_k) vary as a function of film thickness. For thinner films (40-316 nm), the shape of the hysteresis loop is not a square type. Instead, the B-H loops show the characteristics of a "transcritical loop" in which a lower magnetization slope is exhibited prior to saturation and signifies the presence of a perpendicular anisotropy component (PMA) [5]. When the thickness of the films is increased from 40 nm to 100 nm, the H_c and H_k increased to the maximum values of 360 A/m and 1.7 kA/m, respectively. The shape of the hysteresis loops suggests that PMA becomes dominant within this range of film thickness. However, as the film thickness is increased to >100 nm, H_c and H_k start to reduce to the minimum of H_c=64 A/m, H_k=128 A/m for 517 nm thick films. The Fig. 1 (a) illustrate that the shape of the hysteresis loops is entirely transformed into a square type for thicker films. From this analysis, it can be concluded that the state of magnetization is transformed from a perpendicular to an in-plane configuration with an increase of film thickness from 40-517 nm.

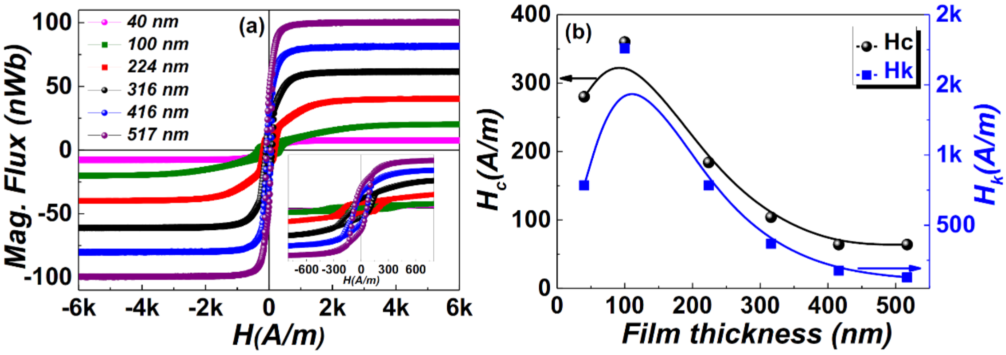

Fig. 1: (a) B-H loops of different films in the as-deposited state. (b) The coercivity (H_c) and anisotropic field (H_k) of as-deposited films as a function of thickness.

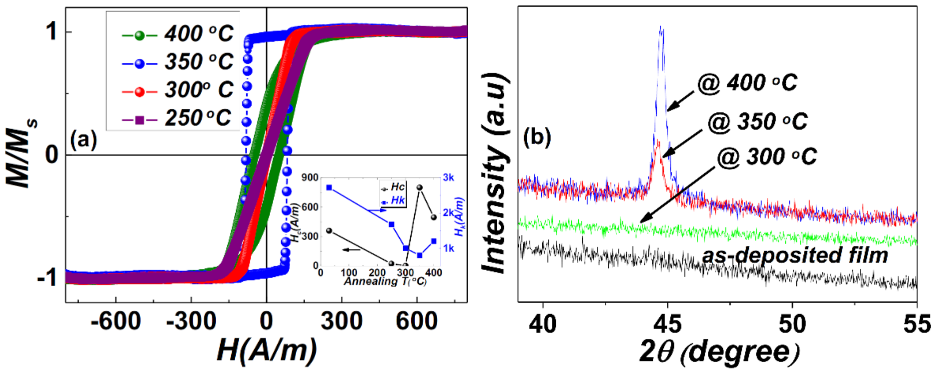

Fig. 2. (a) In-plane hysteresis loops of 100 nm film after annealing. Inset: H_c and H_k of thin films as a function of annealing temperature. (b) X-ray diffraction (XRD) spectrum of annealed films.

The effect of thermal treatment (250-400 °C) on the magnetic properties of 100 nm film is presented in Fig. 2 (a). It illustrates that the state of magnetization is affected by annealing and the transcritical loops, as a consequence, are transformed into a square type with reduced values of H_c and H_k. The hysteresis loops were soft magnetic fully square behavior after a thermal anneal at 250 °C. The BH- loop study shows that annealing at 300 °C further reduced the level of stress in thin films and as a consequence, H_c was reduced to 3 A/m. This investigation clearly shows that heat treatment radically modified the overall structure and gave rise to in-plane magnetization when annealed in the range of

250-300 °C. However, thermal anneal at higher temperatures (350-400 °C) transformed the amorphous phase into a crystalline structure as confirmed by XRD analysis presented in Fig. 2 (b). The H_c values of films with thermal anneal at higher temperatures increased dramatically and can be explained by the emergence of magnetocrystalline anisotropy of the crystalline phase embedded in the amorphous matrix.

The relative permeability (μ_r) along the hard axis direction of 100 nm thin films annealed at 300 °C was significantly higher (μ_r=1763) with a good loss performance over a wide range of frequency (f) (Fig. 3). However, the μ_r decreased with increasing film thickness. The decrease in μ_r of thicker films is due to the increase in shape dependent demagnetizing field along the in-plane direction due to increased film thickness [6].In addition, rapid decrease in μ_r as a function of f was observed for thicker films. This could be attributed to the very low value of H_k obtained for thicker films which allows the magnetization reversal process to proceed by a combination of domain wall motion and domain rotation rather than purely domain rotation alone.

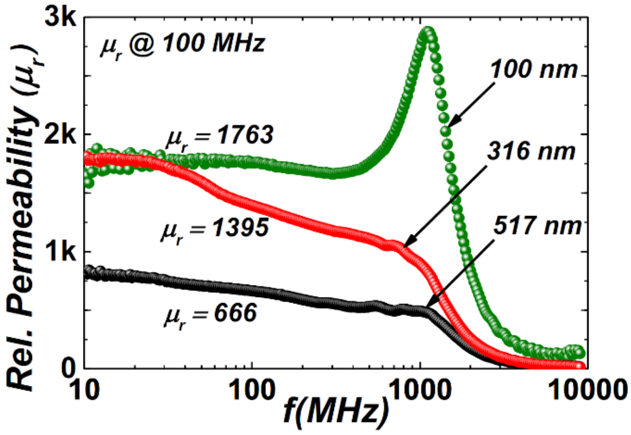

Fig. 3. Permeability as a function of frequency of different films annealed at 300 °C for an hour.

To conclude, thinner films (40-316 nm) of FineMET alloy exhibited a strong perpendicular anisotropy component with large H_c and hysteresis loops with a characteristic transcritical shape. Excellent soft magnetic properties (H_c=3 A/m) were achieved using a thermal annealing at a peak temperature of 300 °C. The high-frequency μ_r of the annealed samples decreased with increasing film thickness and attributed to the demagnetizing field which becomes dominant with film thickness.

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